ISIJ International, Vol. 51 (2011), No. 1, pp. 14–20

Influence of Pellet Basicity (CaO/SiO_2) on Iron Ore Pellet Properties and Microstructure

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(*Received on June 29, 2010; accepted on August 24, 2010*)

In JSW steel limited Pellets form the major part of the iron bearing feed to Corex and Blast Furnace. These two iron making units demand high strength, lower reduction degradation index pellets to maintain good permeability of the bed to achieve high productivity and lower fuel rate. To produce good quality of pellets certain additives are important. JSWSL produces basic pellets with basicity (CaO/SiO_2) 0.40 to 0.50. The quality of the pellet is affected by the type of the raw materials, gangue content, and flux proportion and their subsequent treatment to produce pellets. The limestone addition, *i.e.* basicity–CaO/SiO_2 of pellet decides the mode, temperature and the amount of melt formed. The properties of the pellets are, therefore, largely governed by the form and degree of bonding achieved between ore particles and also by the stability of these bonding phases during the reduction of iron oxides. Hence in production of acid, basic and fluxed pellets, characterization of the bonding and crystalline phases is of prime importance in understanding the basis for the production of pellets of desired quality. To understand the influence of limestone addition (basicity) on iron ore pellets microstructural, physical and metallurgical properties basket trials have been carried out with different level of basicity from 0.08 to 1.15. From the test result it was clear that pellet properties were influenced by the bonding phases present in the pellet. The tumbler index increased from 93.15 to 95.38 % and cold crushing strength increased from 176 to 264 kg/p with increase in pellet basicity from 0.08 to 1.15. This effects result from microstructural differences appeared from the flux addition. RDI of the pellet decreased initially from 16.3 to 10.9 % in the pellet basicty range from 0.08 to 0.33 and again increased from 10.9 to 13.6 with increase in pellet basicty from 0.33 to 1.15. This effect is due to the change in structural properties of the pellet during reduction. Pellet with basicity 0.33 showed good physical as well metallurgical properties due to bonding phases present in the pellets.

KEY WORDS: iron ore pellet; basicity; physical and metallurgical properties; microstructure.

1. Introduction

JSW Steel Limited is operating a 4.2 Mtpa pellet plant to produce pellets for two blast furnaces and two corex iron making units. During processing of pellets in an iron making units, their physical, metallurgical and microstructural properties have a major influence on their reduction behaviour. In general, the main types of pellets for iron making units are acid, basic and fluxed pellets. To produce good quality of pellets certain additives are important. In pelletization process, limestone is employed for modifying the pellet basicity. JSWSL produces basic pellets with basicity (CaO/SiO_2) 0.40 to 0.50. In recent years blast furnace/ Corex iron making units prefers fluxed pellets as iron bearing feed because, fluxed pellets gives precise quality requirements required by the iron making units.

The quality of the pellet is affected by the type of the raw chemical composition, raw material mix proportion, gangue content, and flux proportion and their subsequent treatment to produce pellets. These factors results in variation in the physicochemical properties of coexisting phases, structure, distribution of phases, and porosity in the pellets. The properties of the pellets are, therefore, largely governed by the type and degree of bonding achieved between ore particles and also by the stability of these bonding phases during the reduction of iron oxides. Hence in production of acid, basic and fluxed pellets, characterization of the bonding and crystalline phases is of prime importance in understanding the basis for the production of pellets of desired quality. A limited number of investigations have been done on the bonding in fluxed hematite pellets in the basicity range of 0.5 to 1.00.[1–3] To understand the influence of limestone addition (Basicity) on pellet physical, metallurgical and microstructural properties basic studies have been carried out on hematite iron ore fines with limestone addition from 0 to 7.80 % in the green mix to obtain pellet basicity (CaO/SiO_2) 0.08 to 1.15.

2. Pelletization Process at JSW Steel Limited

Production of iron oxide pellets from iron ore fines involves different steps from drying to induration. The ore fines are initially dried to a moisture content of less than 1 % before being sent to a ball mill for grinding to the required fineness. The ground ore fines are now mixed with other additives like bentonite, limestone, carbon bearing

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sludge and iron ore slurry and then sent to pelletising/balling discs to prepare green pellets/balls. These green pellets are fired in the indurating machine to get the required physical, mechanical and metallurgical properties, making them suitable feed material to iron making units. **Figure 1** shows the schematic diagram of the iron ore pelletization process.

Figure 2 schematically shows the induration process in a straight grate machine. The green pellets, after sizing through a roller conveyor, are discharged onto the travelling grate induration machine on top of the hearth layer and between the side layers of the fired pellets. The hearth layer pellets protect the grate bars from high gas temperatures. The green pellets contain 8 to 9% free moisture and are 8 to 16 mm in size. The travel ling grate carries the pellets through the indurating furnace where they are subjected to the sequential zones of updraft drying, downdraft drying, put, in between preheating and after firing and first and second cooling. The first stage of drying is updraft to prevent the condensation of the water and pellet deformation in the bottom layer of the pellet bed. For updraft drying the hot gas is recycled from the cooling zone 2. The drying is continued in a subsequent downdraft stage to remove free water of the top of the bed by relatively hot gases coming from the firing zone of the furnace. In these two zones it is necessary to use drying air of sufficient temperature to cause rapid water evaporation yet not so high that the pellets are destroyed by high internal pressures. In the preheating zone, the pellets are heated to about 500 to 1 000°C by downdraft air flowing through the bed and the hot gas is recycled from the cooling zone 1. During this stage, pellets are completely dried and reactions such as removal of combined moisture, decomposition of carbonates, coke combustion and conversion of iron oxide to hematite take place.

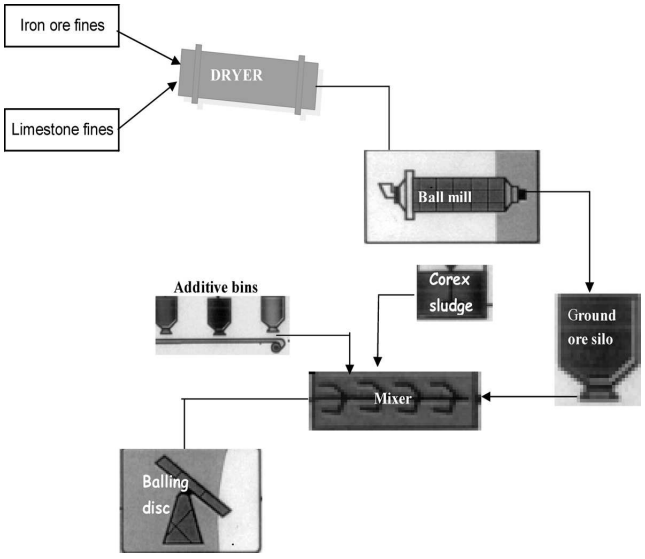

Fig. 1. Schematic diagram of the iron ore pelletization process.

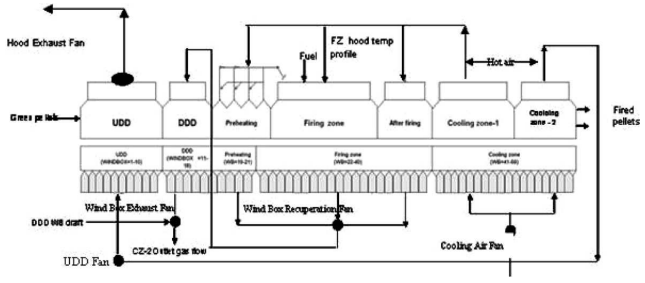

Fig. 2. Schematic diagram of straight grate induration process for iron ore pellets.

The reactions from the preheating zone continue in the firing stage. Here pellet charge is heated to an optimum temperature for a controlled period, and temperature is raised to 1 300°C. Strength of the pellets increases at this stage because of re-crystallization and formation of slag phase. Some of the off-gas from the firing zone is recuperated to the drying zone. Five interconnected process fans are provided to circulate air throughout the different zones of the indurating machine. After firing, the fired pellets undergo cooling where ambient air is drawn upward through the bed. The off-gas leaving the first stage of cooling has a temperature of around 1 000°C, and this gas is gas is directed to the firing and preheating zones where it is further heated by the burners with COREX gas fuel. The gases from the cooling stage 2 are of lower temperature and is used for drying of pellets.

3. Literature Review on Acid and Fluxed Pellets[4)]

The pellets may be acid, partially fluxed, super fluxed according to their acid or basic oxide content.

3.1. Acid Pellets (Basicity (CaO/SiO_2)–<0.1)

In the case of highly acid pellets with a basicity of less than 0.1, the gangue is predominantly present as silica and alumina. The fired pellet strength is, to a certain degree, due to hematite bridges of polycrystalline structure. These pellets contain large amount of open pores. The reduction gas can quickly penetrate through these pores into the pellet core and simultaneously attack the structure in many places. The structural change begins very early at low temperatures over the whole pellet volume.

3.2. Basic Pellets (Basicity (CaO/SiO_2)–(0.1 to 0.6))

During the firing the pellets with low CaO proportions at a basicity of 0.1 to 0.6 a glassy slag phase consisting of SiO_2, CaO, and Fe_2O_3 of varying proportion is formed. Due to increased flux addition, slag formation is to a certain extent and slag bonding with iron ore crystals is common.

3.3. Basic Pellets with Basicity >0.7

If the pellet gangue contains more CaO than corresponds to a basicity of about 0.70, not only glassy phase, consisting of SiO_2, CaO, and Fe_2O_3, but also calcium ferrites, $CaO \cdot Fe_2O_3$, are formed. During pellet firing, the availability of CaO considerably favours the crystal growth of hematite. It should be noted that pellets with a high CaO content and a basicity exceeding about 0.6 have a high mechanical strength after pellet firing.

4. Experimental

Laboratory basket tests were carried out by varying the limestone content from 0 to 7.80% (Basicity 0.08 to 1.15) in the green pellet mix. The raw materials used for the

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Table 1. Raw material chemical analysis.

Description	Mass %			
	Iron ore	Limestone	Bentonite	Corex sludge
Fe (Tot)	64.2	2.24	11.05	27.15
Al_2O_3	2.37	0.67	16.90	6.06
SiO_2	3.20	3.82	48.80	9.80
CaO	0.079	49.87	1.63	5.99
MgO	0.015	1.30	2.75	2.87
LOI	1.98	40.4	8.50	
C				33.89

Table 2. Green pellet mix proportion.

Description	Weight %			
	Mix 1	Mix 2	Mix 3	Mix 4
Iron ore	96.05	94.05	90.55	88.25
Limestone	0.00	2.00	5.50	7.80
Bentonite	0.70	0.70	0.70	0.70
Corex sludge	3.25	3.25	3.25	3.25

Table 3. Green pellet size analysis.

Size, mm	Basicity (CaO/SiO_2)			
	0.08	0.33	0.78	1.15
	Wt, %			
+16	1.3	1.0	0.9	1.3
-16+12.5	19.5	21.1	22.6	20.8
-12.5+10	71.4	72.7	74.0	74.0
-10+8	5.2	4.4	5.5	4.9
-8	2.6	2.9	3.2	1.4

Table 4. Induration machine parameters.

Description	
Feed rate, tph	471
Machine speed, m/min	2.27
bed height, mm	531
Hearth layer, mm	60
Firing temperature, °C	1320
Burn through temperature, °C	320
Gas consumption, Nm^3/tonne of the feed	54.6

preparation of the green pellets are iron ore, limestone, bentonite and Corex sludge. The chemical analysis of the raw material is shown in the **Table 1**. Iron ore fines and limestone of −10 mm size were ground separately in laboratory ball mill. Green pellet mix was prepared by mixing the iron ore fines, limestone, bentonite and Corex sludge as per **Table 2**. Green pellets were prepared using laboratory scale balling disc. The green pellet size distribution is shown in **Table 3**. The details of balling disc are as follows:

Disc diameter: 450 mm

Disc operating angle: 45°

Disc speed: 38 rpm

Each set of experiment comprises firing of 20 kg green pellets. The green pellets were kept in rectangular stainless steel baskets (500 mm long) and fired in pellet plant induration machine. The stainless steel basket was kept in the centre of the pellet bed on the hearth layer and it covers entire bed height of the induration machine. The corresponding operating parameters of the plant are shown in **Table 4**. Induration machine firing profile is shown in **Fig. 3**. Fired pellets were subjected to evaluations of chemical, physical and metallurgical properties. Samples for microstructural investigation were prepared by cold mounting. Polarising microscope and image analyser have been used for microstructural characterisation.

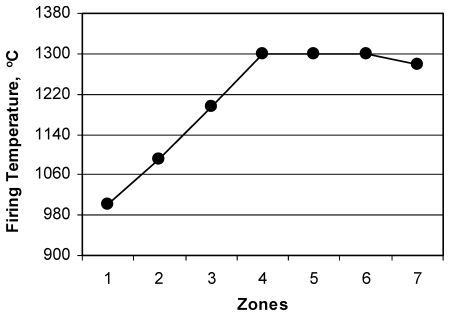

Fig. 3. Firing profile of induration machine.

Table 5. Green Pellet properties.

Description	Basicity (CaO/SiO_2)			
	0.08	0.33	0.78	1.15
Carbon in green pellets, mass %	1.10	1.10	1.10	1.10
Green pellets moisture, mass %	8.5	8.5	8.5	8.5
Drop No, no	14.1	14.3	12.2	11.2
GCS, kg/p	3.0	2.9	2.1	2.0

Table 6. Chemical analysis of fired pellets.

Description	Limestone, mass %			
	0.0	2.00	5.50	7.80
Fe, mass %	64.50	63.13	62.26	60.25
FeO, mass %	0.27	0.45	0.42	0.46
Al_2O_3, mass%	2.66	2.73	2.90	3.02
SiO_2, mass %	3.50	3.96	4.10	4.50
CaO, mass %	0.65	1.30	3.20	5.17
MgO, mass %	0.38	0.42	0.45	0.52
CaO/SiO_2 (B_2)	0.08	0.33	0.78	1.15

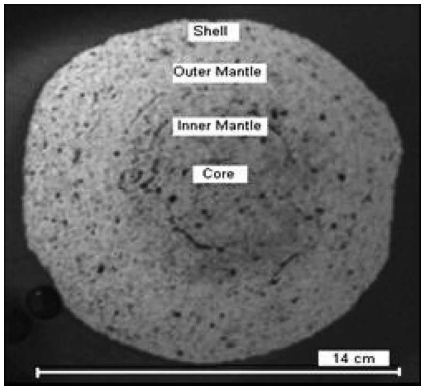

Fig. 4. Segments of pellets.

5. Results and Discussion

The green ball properties and chemical analysis of the fired pellets are shown in **Table 5** and **Table 6** respectively. The firing conditions during the laboratory experiments have been maintained the same. Pellets were subjected to various tests under different conditions to study the physical and metallurgical properties. To understand the effect of basicity on phase formation, microstructural investigation has been carried out.

5.1. Microstructural Investigations

Microstructural investigations were carried out by dividing the pellets into four segments as shown in **Fig. 4**. They are defined as:

(i) Shell: it extends 200 mm below from outer surface (peripheral)

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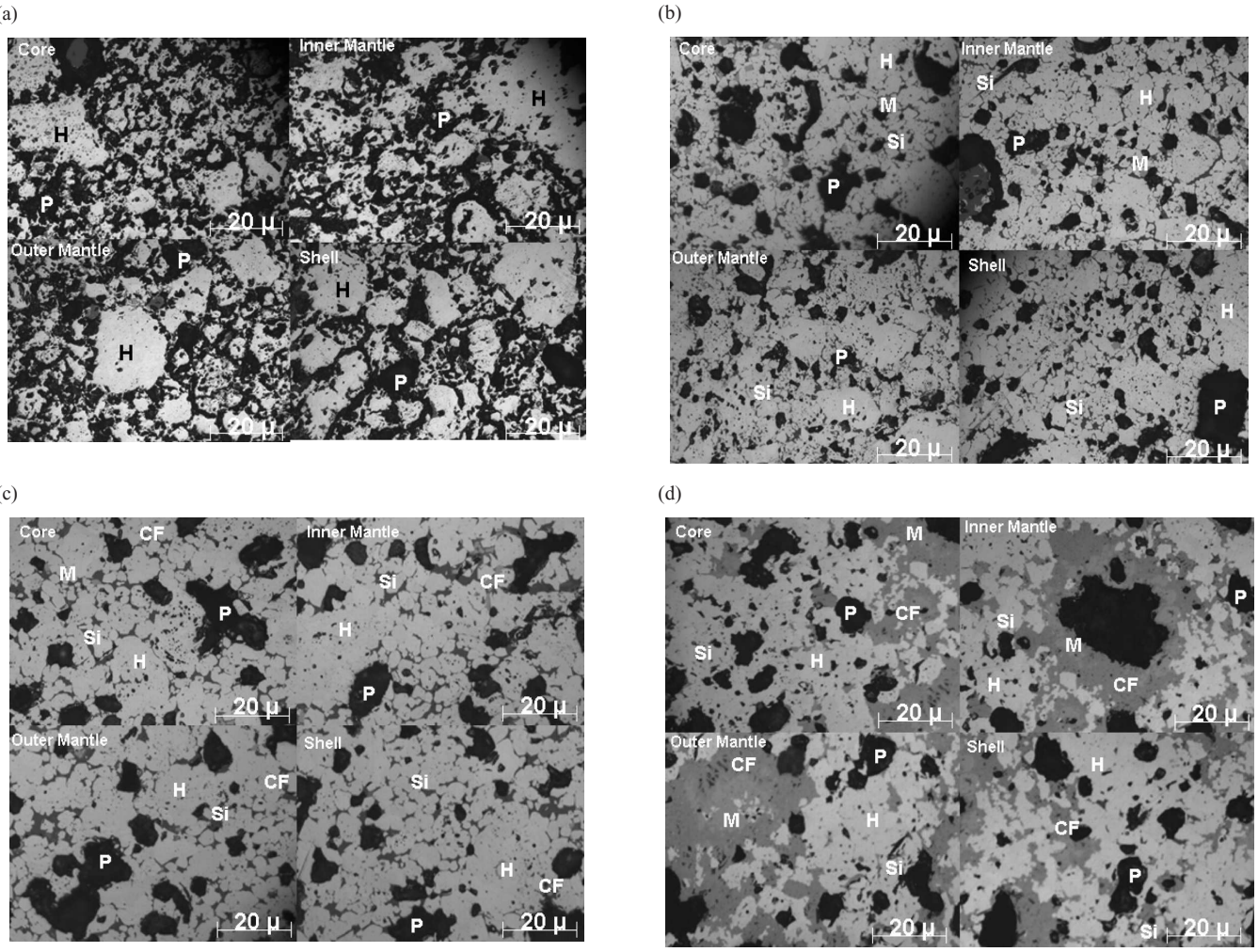

Fig. 5. (a) Microstructure of pellet with limestone: 0% (CaO/SiO_2: 0.08). (b) Microstructure of pellet with limestone: 2.0% (CaO/SiO_2: 0.33). (c) Microstructure of pellet with limestone: 5.50% (CaO/SiO_2: 0.78). 5d Microstructure of pellet with limestone: 7.80% (CaO/SiO_2: 1.15).

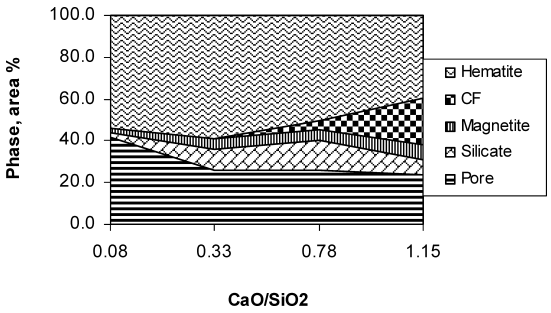

Fig. 6. Microstructural phase analysis.

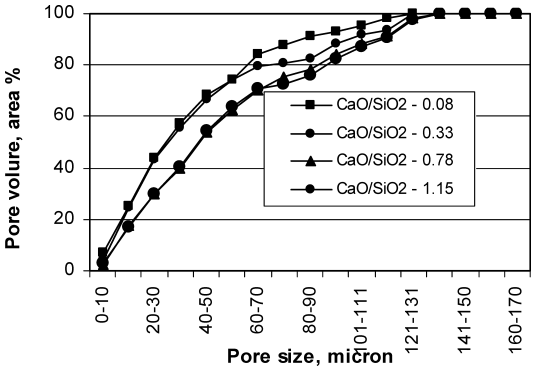

Fig. 7. Pore size distribution.

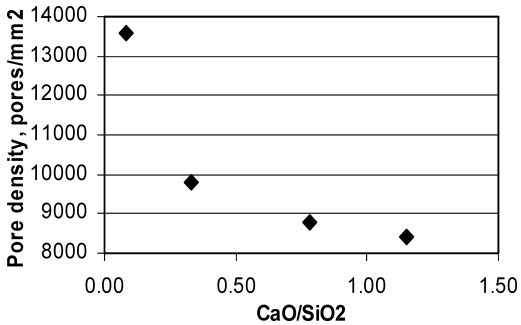

Fig. 8. Influence of basicity on pore density.

(ii) Outer mantle: just below the shell (2 mm thick)
(i) Inner mantle: just below outer mantle (4 mm thick)
(ii) Core: innermost part of the pellet (4–5 mm in diameter).

Primary phases present in iron ore pellets are hematite (grey white) magnetite (grey white with pinkish), slag phase (grey), Calcium ferrites (grey), and pores (black). The microstructures of pellets are presented in Fig. 4.

5.2. Influence of Limestone Addition on Microstructural Properties

Figures 5(a) to 5(d) shows pellet microstructure with limestone addition from 0 to 7.80% (CaO/SiO_2 0.08 to

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Table 7. Chemical composition of microstructural phases (SEM) Minerological phase.

Minerological phase	Basicity (CaO/SiO_2)	Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO
		Mass %				
Hematite	At all basicty pellets	97.71	1.30	0.92	0.07	-
Magnetite	At all basicty pellets	96.98 (Fe_3O_4)	0.00	1.99	0.56	0.00
Calcium ferrite	At basicty 0.78 and 1.15	81.05	4.86	1.20	12.50	0.39
	At basicty 0.33	28.00	41.28	5.25	24.72	0.75
Slag phase	At basicty 0.78	14.00	39.00	4.00	42.92	0.08
	At basicty 1.15	25.60	24.85	4.25	44.45	0.85

1.15). Hematite was the predominant phase in pellets with basicity from 0.08 to 1.15; other phases have varied depending on the basicty of the pellet. **Figure 6** and **Figure 7** shows the microstructural phase analysis and pore size distribution of the pellets respectively. **Figure 8** shows the pore density of the pellets. **Table 7** shows chemical composition of microstructural phases (SEM).

Pellets with 0% limestone *i.e.* natural basicity consists of hematite phase associated with pores from core to shell. The large hematite particles were bonded with small hematite particles. Here small hematite crystals forms the main bonding phase. Natural basicity pellets associated with large number of pores and these pores were internally connected with each other and form the open texture. The presence of minor quantity of free silica was observed in the pellets. (Fig. 5(a) outer mantle).

Pellets with 2.00% limestone (CaO/SiO_2–0.33) associated with hematite, silicate/slag phase and pores from core to shell. The core and inner mantle consists of little magnetite phase. Here we can observe both crystal as well as slag bonding.

Pellets with 5.50% limestone (CaO/SiO_2–0.78) associated with minor quantity of calcium ferrites with other phases like hematite, magnetite, silicate/slag and pore phase. Here also we can observe both slag as well as crystal bonding. Here from core to inner mantle slag bonding was more predominant compared to crystal bonding.

Pellets with 7.80% limestone (CaO/SiO_2–1.15) associated with calcium ferrites, hematite, magnetite, silicate/slag and pore phase. The predominant microstructural phase was hematite. In these pellets outer mantle and shell consists of magnetite phase within the calcium ferrite phase.

Porosity of the pellet decreased with increase in limestone addition from 0 to 7.80% (Basicity 0.08 to 1.15) (Fig. 6). With increase in pellet basicity total pore percentage decreased by decreasing pore density of the pellet (Fig. 8). The pore size (volume percentage) of 110 to 140 micron size increased from 11.6 to 17.5% in the basicity range from 0.33 to 1.15. Pellet with basicity 0.78 to 1.15 consist of round pores and pore assimilation was not taken place.

5.3. Influence of Pellet Basicity on Chemical Properties of the Pellet

Figure 9 shows the influence of limestone addition on pellet basicity. Pellet basicity increased with increase in limestone addition. **Figure 10** and **Fig. 11** shows the influence of pellet basicty on total Fe, FeO and SiO_2 content of the fired pellets respectively. Total Fe content of the pellet decreased and silica content of the fired pellets increased with increase in pellet basicity. Pellet basicty has not shown any significant influence on pellet FeO content in the basicity range of 0.33 to 1.15. The FeO content of the pellet increased initially in the basicity range of 0.08 to 0.33 and after wards not shown any significant influence. FeO content of the pellet was within the target value (below 0.50%) at all basicity level from 0.08 to 1.15.

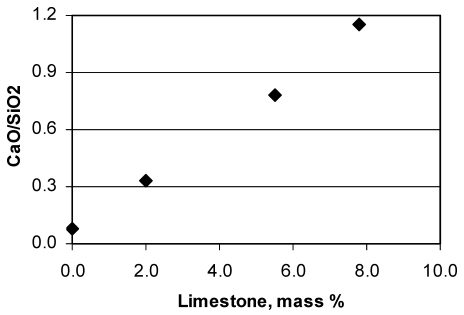

Fig. 9. Influence of limestone addition on pellet basicity.

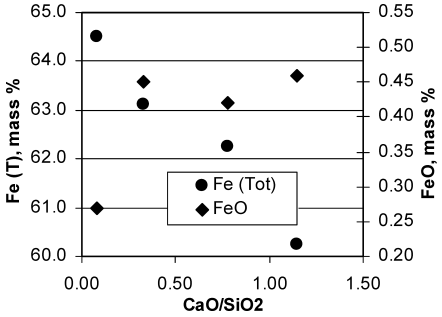

Fig. 10. Influence of basicity on Fe and FeO content of fired pellet.

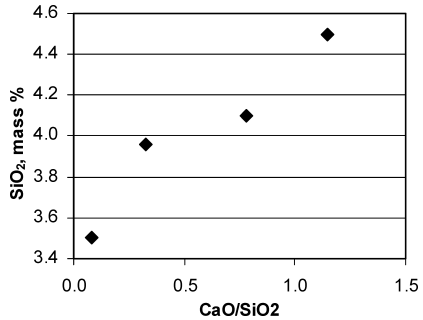

Fig. 11. Influence of basicity on SiO_2 content of fired pellets.

5.4. Influence of Basicity on Physical Properties

Figure 12 and **Fig. 13** shows influence of pellet basicity on physical properties like pellet tumbler and abrasion index and cold crushing strength respecrtively. Pellet tumbler and cold crushing strength increased and abrasion index decreased with increase in pellet basicity. Strength of the pellet mainly depends on the bonding phase as well as pore phase. Pellets of natural basicity forms a monosystem,

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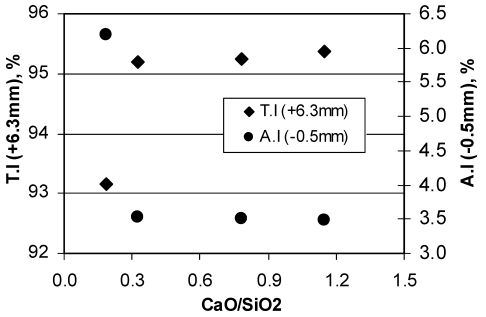

Fig. 12. Influence of basicity on pellet tumbler and abrasion index.

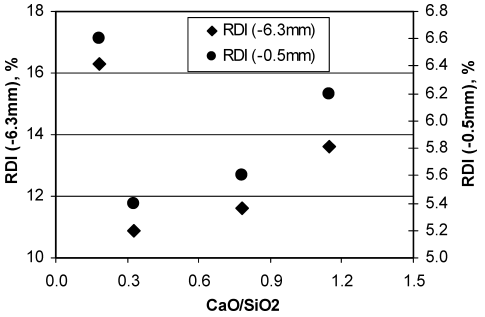

Fig. 15. Influence of basicity on pellet reduction degradation index.

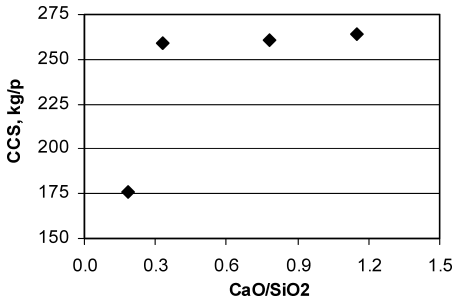

Fig. 13. Influence of basicity on pellet strength.

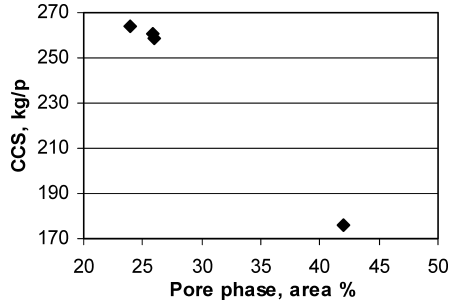

Fig. 14. Influence of pore phase on pellet strength.

where the hematite phase forms the large ore fraction as well as the strengthening binder. At high temperature 1 300°C the small fraction of hematite grains fuse together to form bridge type binder between hematite particles. In this case pore phase plays a major role. **Figure 14** shows influence of pore phase percentage on pellet strength. Pellet CCS decreased with increase in pore phase percentage. The percentage of rounded pores increased from 0 to 48% with increase in bacisity from 0.08 to 1.15. The tumbler index and strength of the natural basicity pellets were poor due to the more open pores. These open pores in the natural basicity pellets were reduced the bonding efficiency of the hematite crystals. Long stretched pores deteriorate the quality of pellets. With bigger pores, the load bearing capacity of pellets decreases due to large strain by the stress concentration at the pore wall. Smaller and rounded pores do not allow stress concentration and lead to good strength.[5] Due to this reason these pellets break down very easily under abrasive loads during transportation.

Fluxed iron ore pellets are more complex than the unfluxed iron ore pellets. On heating, decomposition of limestone, the silicate and ferrites formation takes place based on the degree of fluxing. The melt formation starts at the iron ore-lime interface. Higher limestone 5.00% (basicity 0.78) results in higher amount of the melt at similar heat conditions. At higher basicity 1.15 pellets consist of ferrite phase with hematite and silicate phase. The silicate binder in the pellets of basicity 0.30 to 0.80 was a high silicon glass phase; that in pellets of basicity 1.15 was high calcium glass phase. Melt phase as well as ferrite phase in the pellets provides superior bindng of the pellet particles during induration. Thus high basicity results in superior strength. According to Yusfin and co-workers for all fluxed pellets in the basicity range of 0.30 to 1.20 the compressive strength is very high.[6]

5.5. Influence of Basicity on Reduction Degradation Index

Figure 15 shows the influence of pellet basicity on reduction degradation of the pellets. Pellet with 2.00% limestone (0.33–basicity) shows lower RDI compared to pellet with 0% and 5.00 to 7.80% limestone (basicity 0.8 to 1.15). Natural basicity pellets showed higher RDI compared to pellets with basicity 0.30 to 1.15. Pellets with natural basicity forms a monosystem, which is hematite phase. In this case, the phase transformation of hematite on reduction occurs in the same temperature, time, and gas conditions. As a result, the pellet breaks down simultaneously over its whole volume and generates more fines. Mayer also confirmed similar observation with the acidic pellets.[4]

Pellets with 0.33 to 0.78 basicity shows lower RDI compared to pellets with basicity 1.15. Pellets with basicity 0.33 to 0.78 consist of high silicate glassy binder and pellets with basicity 1.15 consist of high calcium glassy phase. The silicate glass phase decreased with increase in pellet basicity from 0.08 to 1.15 (Fig. 6). During reduction process at lower temperature 800 to 1 000°C the silicate slag in the form of plastic state reduce the stress and at above 1 000°C the metallic frame provides the strength to the pellet. These pellets do not disintegrate on heat treatment during reduction and retains the shape until the metal separated from the slag.

Pellets with basicity 1.15 loose its strength on reduction due to conversion of calcium glass phase into crystallized wollastonite phase ($CaSiO_3$) at around 1 073 to 1 173 K (800 to 900°C). During the conversion cracks forms over the entire pellet mainly at the boundaries of the silicate crystals; these cracks allows the reducing gas to the ore phase. The pellets break down easily because at this temperature wollastonite is in the form of solid state and do not

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reduce the stress arises in the hematite–magnetite–wustite transitions. Gilung *et al.*, and Zhuravlev *et al.*, also confirmed this observation with the fluxed pellets.[7–9)]

6. Conclusions

(1) The FeO content of the pellet increased from 0.27 to 0.45% in the basicity range of 0.08 to 0.33.
(2) Pellet basicity has not shown any significant influence on FeO content of fired pellet in the basicity range of 0.33 to 1.15. The overall FeO level was within the acceptable range *i.e.* below 0.50%.
(3) The tumbler index increased from 93.15 to 95.38% and cold crushing strength increased from 176 to 264 kg/p with increase in pellet basicity from 0.08 to 1.15. These effects resulted from microstructural differences appeared from the flux addition.
(4) RDI of the pellet decreased initially and again increased with increase in pellet basicty. This effect is due to the change in structural properties of the pellet during reduction.
(5) The basicity in the range of 0.33 to 0.78 showed good physical and metallurgical properties of the pellet due to bonding phases present in the pellet. Pellet with basicity 0.33 showed superior properties compared to pellet with basicity 0.78.

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